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FINAL REPORT

PIEZOELECTRIC POLYMER TRANSDUCERS FOR DETECTION OF
STRUCTURAL DEFECTS IN AIRCRAFT

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NAVAL AIR DEVELOPMENT CENTER
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PIEZOELECTRIC POLYMER TRANSDUCERS FOR DETECTION OF
STRUCTURAL DEFECTS IN AIRCRAFT

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ABSTRACT

A new, versatile thin film material, PVF₂ (poly-vinylidene fluoride), has been fabricated into sensors for ultrasonic transducers because of its outstanding piezoelectric properties as well as its mechanical strength and chemical stability. PVF₂ has a compliance ten ~~(10)~~ times higher than that found in ceramics, and its g-constant (voltage per unit stress) is very high. Since the material can be made into very thin films, very wide-band electro-acoustic transducers can be incorporated into sensors that are flexible, variable in shape and a wide range of sizes. This fabrication versatility along with its relatively low cost, and its attractive piezoelectric, mechanical strength, and chemical stability makes this material a prime candidate for a large range of applications to monitor or inspect aircraft structures. A number of inspection techniques have been explored and are discussed. These include acoustic impact testing for ball bearing wear and crack formation in metal structures; pulse-echo and transmission ultrasonics to inspect composites.

This work was performed under the Analytical Rework Program guided by Mr. Martin J. Devine, Associate Director of Special Projects. The program was funded by Naval Air Systems Command (AIR-4114C).

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I. INTRODUCTION

Acoustic emission monitoring, pulse-echo and transmission ultrasonics, acoustical signature analysis, and other related vibration and acoustical tests make use of piezoelectric transducers. However, the piezoelectric crystalline and ceramic materials currently used in sensors are narrow band transducers and hence cannot detect high count rate failure precursors nor yield an undistorted acoustical spectrum of the events being monitored. Polymer transducer based on piezoelectric polymer film offer a number of advantages over conventional transducers. Polymer sensors are flexible and they can be produced in a wide range of sensing areas. They have low density, excellent stability to shock, and the ability to follow severe contours. Polymeric piezoelectric elements can be cemented to surfaces, and because the low-mass, thin-film transducer is spread over a relatively large area, the effect on the surface will be minimal. Polymer film transducers have a high sensitivity and a flat frequency response and are relatively easily and inexpensively fabricated. In Figure I a prototype polymer sensor is shown. Attachments and hardware are of the conventional type, and the system is compatible with conventional electronics.

A. Identification of Problem Areas in Detection and Monitoring the Structural Integrity of Aircraft Components

Among the many non-destructive evaluation tests designed to reveal the presence of harmful defects such as cracks, porosity, inclusions, and similar inhomogeneities are: neutron-, X-, and gamma-radiography, stress analysis, scanning electron microscopy, laser holography, positron annihilation, fiber optics, exo-electron emission, magnetic particles and perturbations, eddy current, and microwave radiation. There are also other methods that deal with the sensing of vibrations and acoustical signals. They include: ultrasonic acoustical image holography, acoustical signature analysis, acoustical-optical imaging,

acoustical impact testing, acoustic emission, pulse-echo and transmission ultrasonics, and eddy-sonic vibration analysis.

We are concerned with the vibration and acoustical methods and in particular discuss the improvement of their operation through the use of a new piezoelectric transducer material. This material is a polymer and has certain properties that should overcome several deficiencies of the present technology. As examples:

(1) There is a detrimental effect on the propagation and reception of signals due to the acoustic mismatch between materials to be tested and/or the bonding agent and the ceramic or crystal transducers now in use.

(2) The very common acoustic impact test, which is suited to detecting delaminations and debonds near surfaces, is very dependent on the operator's skill. The information is difficult to interpret because the usual accelerometers do not yield an undistorted acoustic spectrum of the effect of tapping the test object; the ringing of the transducer is recorded along with the ringing of the test object.

(3) Acoustical signature analysis would also benefit greatly if the transducer had an undistorted sensitive response over a very great frequency range. The current transducers are only sensitive in limited frequency bands of a few tens of kHz.

(4) The monitoring of acoustic emission signals during stress testing or in the field while an object is stressed would be improved if precursor signals could be detected before a crack occurs.

(5) The bonding of transducers to curved and bending components is very difficult. This problem would be eased considerably through the use of a flexible transducer that could be permanently bonded to such a component.

(6) The ultrasonic pulse-echo and transmission inspection process of large areas (such as wing surfaces) is severely handicapped by the small size of current transducers. Large-area transducers could speed up the inspection process considerably.

(7) Ultrasonic imaging techniques could benefit greatly from easily controlled wide-band transducer arrays.

(8) All applications of transducer design would benefit by the existence of an easily and inexpensively fabricated material.

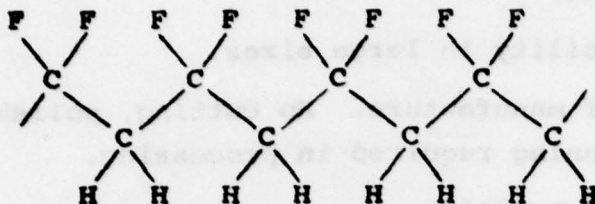
See also Sections II.B, III, and IV in which several more problems are discussed in the light of improved transducer design through the use of polymer piezoelectric material.

B. Properties and Advantages of Polymer Piezoelectric Transducers

As an alternate to the standard piezoelectric crystalline and ceramic materials currently used in acoustic transducers, polymer material offers a new opportunity for expansion of the capabilities of non-destructive evaluations and acoustic interrogations of materials. The polymeric material of choice is poly(vinylidene fluoride), PVF_2 , which is manufactured in the U. S. by Pennwalt Corporation under the trademark, KYNAR®. The presence of fluorine in the fluorocarbon polymer PVF_2 renders this compound inert

to almost every chemical. This inertness, coupled with outstanding weather and heat resistance, and a variety of other useful properties (such as the highest achievable piezoelectric activity among all polymeric materials) make this fluorocarbon unique among polymers. PVF_2 is unaffected by long-term (20 years or more) exposure to sunlight and other sources of ultraviolet radiation. Its combination of low moisture absorption, high chemical resistance, and stability to ultraviolet radiation make it attractive for applications requiring long service life under severe atmospheric conditions. PVF_2 exhibits high tensile and impact strengths, and high resistance to fatigue and creep. It is flexible in thin sections for film, tubing and coated wire. PVF_2 has a broad useful temperature range from below -80°F to 300°F . The upper limit is determined by proximity to the melting point (340°F) and the retention at 300°F of a reasonable level of mechanical strength. PVF_2 exhibits high dielectric strength in thin sections. The combination of high dielectric strength with excellent properties over a broad temperature range has resulted in its use as thin wall primary insulation and as jacketing for aircraft and specialty hookup wire.

The highest piezoelectric response known in polymers is exhibited by PVF_2 films, which, when oriented and given polarization processing like piezoelectric ceramics, display a piezoelectric strain constant ten times greater than that of quartz. PVF_2 is a crystalline high polymer with a degree of polymerization of more than 1000 and crystallinity of more than 40%. Comparisons of piezoelectric and other physical constants among PVF_2 , other polymers, and piezoelectric crystals are illustrated in Tables I and II. The high activity of PVF_2 as a piezoelectric material can be visualized by inspection of the following diagram:



In this diagram of a planar zig-zag polymer segment the fluorine atoms, which are electronegative, lie on one side of the structure, whereas the electropositive hydrogens are on the opposite side. This structure, which corresponds to the β crystal form of PVF_2 , possesses a high degree of polarity, resulting in a high piezoelectric constant. In general, the PVF_2 piezoelectric elements are obtained by stretching the polymer film near its softening point and polarizing it at relatively high temperatures and in a high electric field. Electroding is normally accomplished by vacuum metallizing both sides of the film. Some electrical properties (for thin films at room temperature) in addition to those in Tables I and II that are relevant to transducer applications are:

Volume resistivity = 10^{15} ohm-cm.

Dielectric strength = 1.5-2.0 MV/cm.

Relative dielectric constant (at 1 kHz) = 9-13.

Dissipation factor (at 1 kHz) = 0.03.

PVF_2 transducer elements have a number of advantages over conventional type materials, i.e.,

1. Flexibility and strength.
2. Shock and vibration resistance.

3. Light weight.
4. Low cost.
5. Availability in large sizes.
6. Ease of manufacture. No cutting, polishing, or thinning required in processing.
7. Ease of handling.
8. Variability for special requirements, i.e., response to particular wavelengths.
9. Chemical inertness and non-hygroscopicity.
10. Photochemical and thermal stability.
11. Low thermal conductivity.
12. Large signal output achievable by large areas.

The piezoelectric "gd product" (see Tables I and II) is three times higher than PZT ceramic; consequently very high voltage sensitivities result. Also, the density of PVF_2 is one-fourth and its elastic compliance (the inverse of Young's modulus) is twenty-eight times that of ceramic. PVF_2 is the first practical piezoelectric material that is soft and flexible.

The electromechanical, thermal, rheological, and chemical properties of this polymer material allow the making of electroacoustic transducers of simple construction and superb characteristics for wide-band audio equipment. The potential of this material has also been demonstrated in acoustic emission and imaging, hydrophones, accelerometers, pressure sensors, intrusion detectors, and numerous other transducer applications.

Table I. Typical Piezoelectric Constants for
Industrial Polymers

	d_{31} (10^{-12} m/V)	g_{31} (10^{-3} V.m/N)
poly(vinylidene fluoride)	20	190
poly(vinyl fluoride)	2	20
poly(vinyl chloride)	1	15
polycarbonate	0.5	18
nylon-11	0.5	15
polyacrylonitrile	1	23
poly(vinylidene fluoride) mixed with PZT powders	20	45

The coordinates employed for the sample films are as follows: the 1-axis is the direction of elongation, the 3-axis is perpendicular to the film surface, and the 2-axis is perpendicular to both 1 and 3 axes. The constant, d_{31} , indicates the polarization in the 3-axis produced by the tensile stress in the 1-axis. The constant g_{31} is given by $g_{31} = d_{31}/\epsilon_3$, where ϵ_3 is the dielectric constant in the 3-axis.

Table II. Comparison of Physical Constants between Piezoelectric Crystals and PVF₂

	density ρ (10^3 kg/m^3)	dielectric constant ϵ/ϵ_0	piezoelectric strain constant d (10^{-12} m/V)	voltage output coefficient g (10^{-3} V.m/N)	coupling coefficient k (%)	acoustic impedance ρc ($10^6 \text{ kg/m}^2 \cdot \text{sec}$)
Quartz 0°X (LE)	2.65	4.5	2.0	50	10	14.3
Rochelle salt 45°X (LE)	1.77	350	275	90	73	5.6
BaTiO ₃ ceramic (LE)	5.7	1700	78	5.2	21	30
PZT ceramic (LE)	7.5	1200	110	10	30	30
PVF ₂ (LE)	1.76	12	20	190	14	1.9

LE = Length Extensional Mode

II. DEVELOPMENTS AND RESEARCH PROGRAMS UTILIZING PIEZOPOLYMERS FOR DETERMINING THE INTEGRITY OF METAL AND LAMINATED STRUCTURES

At the present time there are several research and development efforts utilizing PVF₂. These programs are directed toward perfecting polymeric transducer designs and measuring techniques so as to effectively advance the state of the acoustic interrogation technology.

Among the groups that have provided information on their research efforts are: General Electric Corporation, National Bureau of Standards, Stanford University, Stanford Research Institute, Pennwalt Corporation, and the Naval Air Development Center.

Polymers have certain properties that make their use advantageous in particular types of measurements. There are some cases of considerable importance for which polymer instruments are uniquely suited. Usually the advantages of polymer instruments show up in dynamic measurements. Cementing a small piece of polymer film to a metal sheet will not change the surface density significantly, and hence the amplitude of vibration and the variation of vibration level with frequency measured by the polymer are representative of what the level at the point would be with no instrument attached. Hence it is practical to distribute several polymer vibration gages over a panel surface and deduce the mode of vibration of the panel under various conditions. The noise signatures of bearings, gears, and transmission systems can also be studied with polymer transducers. The mass of a conventional instrument introduces a set of resonances that confuse the noise spectrum being studied and hence may hide the changes in the spectrum that indicate the first signs of deterioration. Also remounting a sensor for each measurement of a vibration spectrum may produce changes in the spectrum due to small changes in mounting conditions;

these may be confused with the changes due to bearing deterioration. Permanent mounting of a sensor to each bearing is preferable for this reason, and also because the low cost and low mass of polymer sensors make permanent attachment economically feasible. Furthermore, through electrical switching automated measurement of many bearings is possible.

Prototype systems and measurements demonstrating the feasibility of these ideas have already been carried out and lend credence to continuation of effort. A polymer transducer for measuring vibration of ball bearings was mounted directly on a curved surface and performed successfully.¹ PVF₂ film transducers are being used to detect propagation of acoustic waves across a large metal plate in order to discern direction and location of acoustic source and defects.²

A program has been started to develop a non-destructive evaluation method using piezoelectric polymer transducers and Fourier transform vibrational spectroscopy.¹ It was found that the mass and modulus of the PVF₂ transducer was so small that the principal vibrational modes of an acrylate bar tested were not disturbed. The spectra obtained from the vibration, which were excited by dropping steel balls or impacting the object with a pendulum bob, were interpretable in terms of normal vibrations. Introducing a defect into the bar caused changes at the dominant frequency and resulted in greater coupling of energy into modes that were only weakly excited in the absence of the defect.

We examined³ the frequency spectrum elicited by having a steel ball strike a riveted aluminum tensile bar that had been stressed at N.A.D.C. approximately two million times until a crack developed under one of the rivets. The electrical signal from

1. National Bureau of Standards, Gaithersburg, Md.

2. Naval Air Development Center, Warminster, Pa.

3. Pennwalt Technological Center, King of Prussia, Pa.

an attached PVF₂ thin film transducer was captured by a commercial multichannel digital recorder and fast Fourier transform analyzer. Qualitative differences in the spectra before and after the crack had been enlarged (by further stressing) were apparent.

Studies have been made using PVF₂ sensors to detect acoustic emission from stressed metal specimens.² Single highly damped pulses with almost negligible ringing produces: (a) in a ceramic transducer a ringing waveform of considerable duration, and (b) in a PVF₂ transducer a single pulse with rapid ring-down. Such excitation pulses produce a signal from the detector for which the frequency spectrum will be proportional to the frequency response curve of the transducer. Thus the conventional narrow band ceramic transducer has a prolonged response to a given excitation, whereas the PVF₂ transducer has a response that itself approximates the excitation pulse. Monitoring tests using PVF₂ transducers have indicated the existence of an emission-rate-related failure precursor in graphite/epoxy and a frequency-shift-related failure precursor in boron/aluminum. Acoustic-emission-signature-analysis testing has identified PVF₂ as a promising transducer material for use in acoustic emission sensors. Attractive characteristics of the material include light weight, high sensitivity, flat frequency response, and low fabrication cost. Comparative experiments led to the conclusion that PVF₂ is not only a practical acoustic emission transducer, but is actually preferable to conventional acoustic emission sensors for certain applications.

Acoustic imaging devices are being developed for detecting defects in metal parts of aircraft engines. There are plans for incorporating PVF₂ into the imaging device.⁴ The laboratory that

2. Naval Air Development Center, Warminster, Pa.

4. General Electric Corporation, Schenectady, N. Y.

has developed acoustical-optical imaging utilizing an ultrasonic camera has plans for examining PVF₂ film transducers to this end.⁵

Plans are underway to incorporate PVF₂ transducers into programs for testing ceramic turbine blades having curved surfaces. It is feasible to install PVF₂ transducers at numerous junctions and diffusion bondings in aircraft. Then large areas can be tested in fractions of a second. Thus the testing time can be shortened, and the accuracy can be increased. Interdigital surface wave transducers are under development.⁶ Surface waves can be excited (generated) and used to detect surface imperfections and interfacial structures on various materials. Interdigitated transducers can be easily fabricated from PVF₂; they would be efficient, tuned, variable frequency generators of acoustic signals. Microspaced photolithographic arrays can be deposited with uniform spacings 8-15 μ m wide. Then sound waves from 40-200 MHz can be produced. (The higher the frequency, the greater the resolution of microstructures.) At these ultra-high frequencies microcracks could be detected. Also at the higher frequencies steerable bulk shear waves can be produced. These waves are important in imaging work and in testing the integrity of bonds and interfacial laminations.

III. PROPOSED APPLICATIONS OF POLYMER TRANSDUCERS TO ADVANCE THE INSPECTION AND MONITORING CAPABILITIES OF NAVAL AIR FACILITIES AND AIRCRAFT MANUFACTURING SITES

A. Identification of Possible Applications of Polymer Transducers to Aid the Inspection Procedures of Naval Air Rework Facilities

Contacts with Code 340 personnel at the Naval Air Rework Facility, Jacksonville, Fla., and the Naval Air Engineering

5. Stanford Research Institute, Menlo Park, Calif.
6. Stanford University, Palo Alto, Calif.

Center, Lakehurst, N. J.. have identified a number of inspection techniques that could be improved through the use of novel PVF₂ transducer configurations. They are outlined in the following paragraphs.

Ultrasonic pulse-echo techniques, in both the longitudinal and shear wave modes in the MHz range, are used to evaluate structural parts of aircraft for crack-like defects and to inspect engine components, airplane wing skins, and supporting machined stiffeners. Polymer transducer elements can be prepared with selectively activated areas; hence shear waves can be generated, controlled, and detected utilizing sensitive PVF₂ material.

The flexibility of PVF₂ transducers would allow them to conform to odd-shaped surfaces. This would expedite the evaluation of various machines having curved and irregular shapes.

Piezo-polymer transducers would be highly advantageous for inspecting airplane wing surfaces. A PVF₂ thin film transducer with an area eight inches square would facilitate inspection procedures that currently utilize a one-half inch square ceramic transducer.

In addition to identification of the above areas of applicability, an assessment of propulsion systems applications for PVF₂ as a new transducer material was initiated with personnel of the Naval Air Propulsion Test Center, Trenton, N. J.

B. Applications of Polymer Transducers in the Evaluation and Monitoring of Helicopter Structures

There are several problem areas in the monitoring of helicopter components in which conventional accelerometers and crystal or ceramic transducers are difficult, if not impossible, to use. Some of these areas may benefit from the application of monitoring and pulse-transmission or

pulse-echo devices fabricated from polymer piezoelectric transducers.

The high sensitivity and flexibility of polymer transducers makes them particularly suited for:

- (1) Monitoring the fatigue life of the helicopter rotor hub and vertical shaft.
- (2) Monitoring the bending of flexible shaft single-rotor aircraft.
- (3) Detecting the delaminations in rotor blades.
- (4) Detecting impending structural failures in hinges and landing gears.

Besides having a high sensitivity in the thickness-compressional and lateral-stretching modes, PVF_2 piezopolymer also has a response in a bending mode. It is apparent from some of the above applications that it would be very useful to develop a device that makes use of the bending sensitivity of PVF_2 piezopolymer.

In the following two sections we outline several particular applications of PVF_2 piezoelectric sensors to the needs of Boeing-Vertol and Sikorsky, two helicopter manufacturers.

1. Feasibility of Utilizing PVF_2 Transducers in the Boeing-Vertol High Frequency Vibration-Monitoring Incipient Fault Detection System

Boeing-Vertol has developed high frequency vibration sensors and peripheral data processors that make use of the resonance of a PZT ceramic transducer to detect periodically occurring sharp-rise-time signals emanating from cracks or spalls in the bearing elements or bearing race or other defects in helicopter transmissions. The Boeing system is based on the transducer's resonance occurring between 20 kHz and 300 kHz.

It would be useful to replace the ceramic with polymer transducer because the PVF_2 transducer is inherently more sensitive, less expensive to fabricate, and can be made in a variety of sizes and shapes. However, the resonance of PVF_2 in its thickness mode of vibration is higher than 10 MHz. Other than increasing its thickness by a factor of 30, another mode of vibration (the lengthwise vibratory mode) can be utilized. This mode has already been successfully employed in an electret condenser phonograph cartridge. It has a flat and highly responsive sensitivity to d.c. up to 40 kHz. Note that the actual (high frequency) resonance can be controlled by tailoring the lateral dimensions of the polymer thin film transducer.

Another conceivable method for detecting the fast-rise-time signals from cracks or similar defects is to utilize the flat frequency response of PVF_2 piezofilm. In the form of a thin film, the PVF_2 transducer (in its thickness mode) has a frequency independent transfer function ranging from 0 Hz up to 50 MHz. Proper design of supporting system electronics then permits a real-time defect signature to be detected and analyzed.

2. Development and Application of Polymer Transducers to Sikorsky's Materials-and-Structures Inspection Needs

The Materials and Structures Department of the Sikorsky Helicopter Company is responsible for inspecting high stress areas, for monitoring and detecting crack development during fatigue testing, and for carrying out ultrasonic inspection of under-cured bonds, weak bonds, and voids in aircraft structures. We believe that transducers fabricated from PVF_2 can assist and improve this inspection program.

Thin polymer sensors can be distributed over the surface of a helicopter structure. Because their mass is low, the specimen or helicopter component is not loaded. Furthermore, because of the polymer's high internal damping, no ringing occurs; thus the acoustic spectrum will not be influenced by the sensor.

Polymer film transducers have high gain and a flat frequency response. In comparative tests on tensile specimens, polymer transducers detected more acoustical activity than ceramic transducers and were able to detect precursors that are unobservable with ceramic transducers. The use of highly sensitive wide band polymer sensors should make it possible to determine the moment of crack initiation and follow the development of material defects through their accompanying acoustic emission.

IV. CONCLUSIONS AND RECOMMENDATIONS

A new and versatile transducer material has been identified: polymeric, piezoelectric, thin film made from poly(vinylidene fluoride), PVF_2 . The properties of this material have been studied, and a great variety of sensors have been fabricated. Initial usage tests have yielded encouragement that PVF_2 has characteristics that in many cases make it the transducer material of choice over ceramic and crystal piezoelectrics for monitoring the structural integrity of aircraft components. PVF_2 transducers are inexpensive; they have low density and excellent stability to shock; they can be permanently installed on structural components; they can be made in large sizes and in arbitrary shapes; the flexible piezo-polymer can conform to flexible and irregularly shaped objects; the thin-film piezo-electrics are necessary for high frequency transducer operation; the acoustic impedance of polymer matches well with various materials to be tested; they are easily fabricated into laminates with other materials.

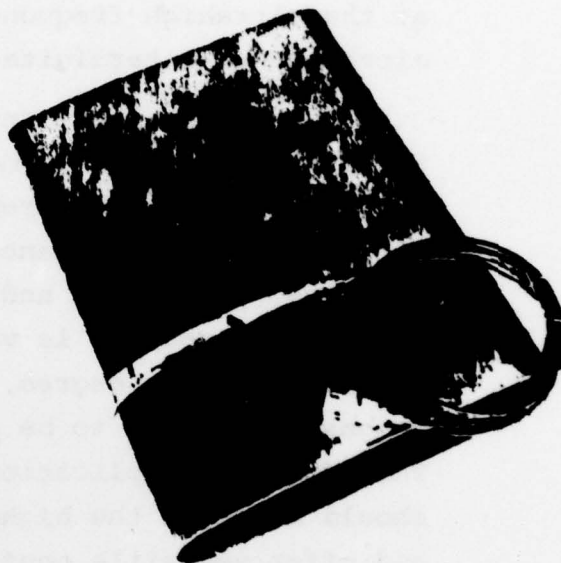
Because PVF₂ has a low mass, the pattern of vibration of a plate is unaffected by the attachment of a polymer transducer. The PVF₂ transducer does not resonate and so has a flat frequency response over a wide range (0-50 MHz). It can be used to generate surface waves and detect surface imperfections and structures within laminates. Microcracks should be detectable at the ultrahigh frequencies that should be producible from micro-spaced interdigitated transducer arrays.

Several applications of polymer transducers for improving the evaluation and the monitoring of aircraft structures have been proposed in this report. Each application requires that one determine and enhance the electrode and poling configuration, the size, thickness, and acoustical mode that would be optimal. Because the polymer is very workable, its properties can be tailor-made to a degree. Acoustic emission analysis has already demonstrated PVF₂ to be practicable and the material of choice. Therefore the application of PVF₂ to this monitoring technique should be given the highest priority. Because they are low cost and offer versatile configurations, PVF₂ transducers should be studied as replacements for ceramic transducers where possible. The flexible parts of aircraft (wings, shafts, etc.) cannot be monitored with conventional transducers. There should be encouragement for the development and application of the bending piezoelectric mode of PVF₂ to the monitoring of the straining of flexible aircraft components.

A program should help develop polymer transducer Fourier transform spectroscopy so that it could be the standard adjunct to acoustic and impact testing. Finally, the development of PVF₂ as a transducer in acoustical imaging and acoustical-optical imaging should be encouraged because this is a promising application to the monitoring of structural integrity.



(a)



(b)

Figure 1. Prototype PVF_2 Polymer Transducer with Cable Attachment and Positioned on:
 (a) Ball Bearing; (b) Section of Titanium Spar from Helicopter Rotor Blade